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MULTIPLE MUONS FROM NEUTRINO-INITIATED MULTI-W(Z) PRODUCTION*

D.A. Morris[1†] and A. Ringwald[2‡]
[1] University of California, Los Angeles, CA 90024, U.S.A.
[2] CERN, CH-1211, Geneva 23, Geneva, Switzerland

ABSTRACT

Current underground detectors can search for multiple muons from multi-W(Z) production initiated by ultrahigh energy neutrinos from active galactic nuclei. O(μb) cross sections give rise to downward going muon bundles whose features differ from those of atmospheric muon bundles.

1. INTRODUCTION

A variety of recent theoretical results has suggested the intriguing possibility that the cross section for the nonperturbative production of O(α_W^{-1}) $\simeq 30$ weak gauge bosons (W,Z) may be as large as $O(100$ pb $- 10\ \mu$b$)$ above a parton-parton center-of-mass threshold in the range 2.4–30 TeV [Ri90,Es90, Mc90,Co90,Ri91a]. Unfortunately, the theoretical evidence is largely circumstantial and so it remains an open question as to whether or not large cross sections for multi-W(Z) production are realized in Nature. Though the SSC, LHC and Eloisatron can address this issue conclusively[Fa90,Ri91b], it is natural to ask whether ultrahigh energy cosmic rays can preemptively confront these conjectures.

1.1 Proton and Neutrino Induced Interactions

If nonperturbative multi-W(Z) production exists, it can be induced by energetic collisions between any two weakly interacting partons ($e.g.,\ q, e, \nu$). Characteristic byproducts of multi-W(Z) processes are energetic prompt muons from W(Z) decays. For example, if 30 W bosons are produced then one can expect $O(30 \times$ Br$(W \to \mu\nu_\mu)) \simeq 3$ prompt muons which may be observed in deep underground detectors.

Multi-W(Z) production induced by cosmic protons is plagued by small rates and poor signatures due to competing generic processes with $O(40$ mb$)$ cross sections[Mo93]. By contrast, multi-W(Z) production induced by ultrahigh energy neutrinos competes only with relatively small O(nb) charged-current reactions. If the multi-W(Z) contribution to the neutrino-nucleon total inelastic cross section $\sigma_{\rm tot}^{\nu N}$ is also of O(nb), then near-horizontal muon bundles provide a signature of neutrino-induced multi-W(Z) production in the rock surrounding underground detectors[Mo91,Be92]. Large underwater detectors like DUMAND and NESTOR would also be

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†email: morris@uclahep.physics.ucla.edu
‡email: ringwald@cernvm.cern.ch

sensitive to such signals[Mo91,Be92,De92]. In this paper we broaden the prospects for detecting or constraining neutrino-induced multi-W(Z) phenomena in underground detectors by suggesting searches for neutrino-induced muon bundles away from the horizontal direction.

To be quantitative we adopt a working hypothesis[Ri91b] which parameterizes the sudden nonperturbative onset of multi-W(Z) production in parton-parton subprocesses by

$$\hat{\sigma}_{\text{multi-W}} = \hat{\sigma}_0 \, \Theta(\sqrt{\hat{s}} - \sqrt{\hat{s}_0}). \tag{1}$$

For purposes of illustration we will consider the production of 30 W bosons by exploring parton-parton center-of-mass thresholds in the range $\alpha_W^{-1} M_W \simeq 2.4$ TeV $< \sqrt{\hat{s}_0} < 30$ TeV and point cross sections 100 pb $< \hat{\sigma}_0 < 10$ μb.

2. MULTI-W MUON BUNDLES INDUCED BY NEUTRINOS FROM AGN

2.1 Constraints on Multi-W Phenomena

Apart from the speculative nature of multi-W production, we must also contend with a lack of knowledge of the flux of ultrahigh energy cosmic neutrinos. A quark-neutrino center-of-mass threshold of 2.4 TeV corresponds to a neutrino energy of ~ 3 PeV where a recent models have predicted a sizeable neutrino flux from active galactic nuclei[St91,St92]. Regardless of any model, the Fly's Eye array puts upper limits[Ba85] on the product of the flux times total cross section for weakly interacting particles (which we will assume are neutrinos) in the range 10^8 GeV $\leq E_\nu \leq 10^{11}$ GeV if such particles initiate extensive air showers deep in the atmosphere. The limit applies only for $\sigma_{\text{tot}}^{\nu N}(E_\nu) \leq 10$ μb since the possibility of flux attenuation is neglected.

Explicit parameterizations of the Fly's Eye limits, which we denote by $(j_\nu \sigma_{\text{tot}}^{\nu N})_{\text{FE}}(E_\nu)$, may be found in Refs. [Ma90,Mo91]. If one considers a particular flux model $j_\nu^{\text{model}}(E_\nu)$ then in the $(E_\nu, \sigma_{\text{tot}}^{\nu N})$ plane the Fly's Eye excludes regions bounded by

$$10^8 \text{ GeV} < E_\nu < 10^{11} \text{ GeV}, \qquad \frac{(j_\nu \sigma_{\text{tot}}^{\nu N})_{\text{FE}}(E_\nu)}{j_\nu^{\text{model}}(E_\nu)} < \sigma_{\text{tot}}^{\nu N}(E_\nu) < 10 \ \mu\text{b}. \tag{2}$$

These inequalities may be translated into a corresponding excluded region in $(\sqrt{\hat{s}_0}, \hat{\sigma}_0)$ space which parameterizes multi-W phenomena. Fig. 1 shows the excluded region of multi-W parameter space for the (revised) flux of Stecker *et al.*[St91]; also indicated are the contours of constant detection rates of multi-W muon bundles containing two or more muons. These rates are integrated over all zenith angles assuming standard muon energy-range relations with a detector depth of 3700 hg/cm^2 and an idealized spherical Earth[Mo93].

For a 72 m $\times$ 12 m $\times$ 4.8 m detector (MACRO) a vertical flux of 10^{-13} cm^{-2} s^{-1} corresponds to 26 events per year. Consider two scenarios within reach of such a detector: $\hat{\sigma}_0 = 10$ nb, 10 μb for a common threshold of $\sqrt{\hat{s}_0} = 2.4$ TeV. These cases correspond to total bundle detection rates of 1.6×10^{-15} cm^{-2} s^{-1} and 3.2×10^{-13} cm^{-2} s^{-1} respectively. As may be inferred from Fig. 2a, as $\hat{\sigma}_0$ increases, the zenith angle distribution of muon bundles becomes less pronounced in the near-horizontal direction and becomes more like the distribution of background atmospheric bundles. However, as seen in Fig. 2b, the relatively small pairwise separation between multi-W muons may distinguish them from atmospheric muons which have much larger separation[Be89,Ah92].

Fig. 1: Region of multi-W parameter space excluded (shaded) by Fly's Eye assuming the flux of Stecker *et al.* [St91]. Dashed lines indicate constant multi-W muon bundle flux (in cm^{-2} s^{-1}) for detector depth of 3700 hg/cm^2.

Another feature of prompt muons from multi-W(Z) processes is their large energy. The average muon energy at the detector (depth 3700 hg/cm^2) is 50 TeV (150 TeV) for $\hat{\sigma}_0 = 10\ \mu$b (10 nb). Muons of this energy have a large probability of undergoing catastrophic energy loss as they pass through underground detectors[Al92, Me92]. In view of these characteristics, current underground experiments should not constrain their searches for AGN neutrinos to looking only in the near-horizontal direction: they can also search for multi-W interactions by looking for energetic, spatially compact muon bundles closer to the zenith.

An additional technique for discriminating multi-W muon bundles from generic muon bundles exploits the presence/absence of associated extensive air showers. Surface arrays like those at EAS-TOP and Soudan-II can furnish valuable information in this context. Even for the largest $O(10\ \mu$b) cross sections we contemplate, over 99% of the corresponding vertical muon bundles originate from multi-W interactions in the Earth. Hence energetic muon bundles without an associated air shower provides an especially convincing signature. The limiting factor in such searches is the solid angle subtended by a surface array.

Fig. 2: Multi-W muon bundles detected at a depth of 3700 hg/cm^2 assuming the flux of Stecker *et al.* [St91]. Shown are curves for $\hat{\sigma}_0 = 10$ nb (solid) and 10 μb (dashed) for a common threshold of $\sqrt{\hat{s}_0}$ = 2.4 TeV. a) Zenith angle distribution of bundles integrated with respect to $\cos\theta$. b) Distribution of pairwise muon separation. The solid histogram corresponds to normalized MACRO data (from two supermodules) from Fig. 4 of Ref. [Ah92]. Roughly 10% of the bundles are dimuons and 90% are trimuons.

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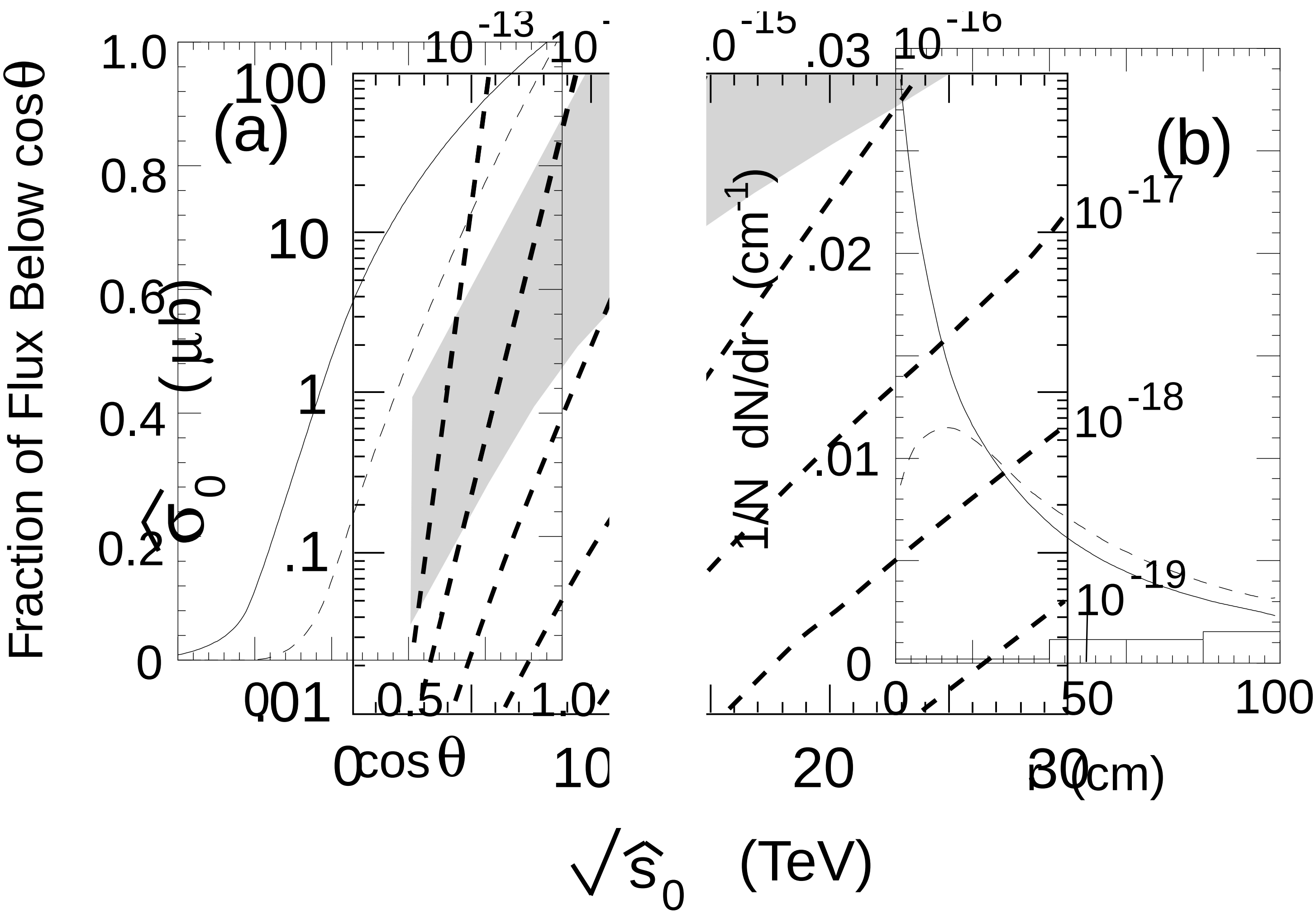

Fraction of Flux Below cosθ
1.0
0.8
0.6
0.4
0.2
0
(a)
(b)
cos θ
1/N dN/dr (cm^{-1})
r (cm)
σ_0 (μb)
$\sqrt{\hat{s}_0}$ (TeV)